DOE Final Report on "Understanding and Constraining the Midlatitude Cloud Optical Depth Feedback in Climate Models"

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Understanding and Constraining the Midlatitude Cloud Optical Depth Feedback in Climate Models

The objective of the research was to better understand the role of ice clouds in climate. I summarize here the conclusions of the 6 papers in the refereed literature and 1 book chapter that were supported by this grant. The early work from 2015 and 2016 is being well cited. It is too early to tell on the most recent publications. The grant supported the work of 3 different graduate students at different times (McCoy, Wall and Berry) Post-doctoral researcher Blaž Gasparini was also partially supported on this grant and led our collaboration with PNNL scientists. PNNL scientists also collaborated in the work of graduate student Wall (Po-Lun Ma).
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McCoy, D.T., D.L. Hartmann, M.D. Zelinka, P. Ceppi and D.P. Grosvenor, 2015: Mixed-phase cloud physics and Southern Ocean cloud feedback in climate models. *J. Geophys. Res. Atmos.* , , doi: 10.1002/2015JD023603, 9539-9554. PDF (50 citations)

Increasing optical depth poleward of 45° is a robust response to warming in global climate models. Much of this cloud optical depth increase has been hypothesized to be due to transitions from ice-dominated to liquid-dominated mixed-phase cloud. In this study, the importance of liquid-ice partitioning for the optical depth feedback is quantified for 19 Coupled Model Intercomparison Project Phase 5 models. All models show a monotonic partitioning of ice and liquid as a function of temperature, but the temperature at which ice and liquid are equally mixed (the glaciation temperature) varies by as much as 40 K across models. Models that have a higher glaciation temperature are found to have a smaller climatological liquid water path (LWP) and condensed water path and experience a larger increase in LWP as the climate warms. The ice-liquid partitioning curve of each model may be used to calculate the response of LWP to warming. It is found that the repartitioning between ice and liquid in a warming climate contributes at least 20% to 80% of the increase in LWP as the climate warms, depending on model. Intermodel differences in the climatological partitioning between ice and liquid are estimated to contribute at least 20% to the intermodel spread in the high-latitude LWP response in the mixed-phase region poleward of 45°S. It is hypothesized that a more thorough evaluation and constraint of global climate model mixed-phase cloud parameterizations and validation of the total condensate and ice-liquid apportionment against observations will yield a substantial reduction in model uncertainty in the high-latitude cloud response to warming.

McCoy, Daniel T., Ivy Tan, Dennis L. Hartmann, Mark D. Zelinka and Trude Storelvmo, 2016: On the relationshps among cloud cover, mixed-phase partioning and planetary albedo in GCMs.*JAMES,* , 8, doi:10.1002/2015MS000589. PDF (36 citations)

In this study, it is shown that CMIP5 global climate models (GCMs) that convert supercooled water to ice at relatively warm temperatures tend to have a greater mean-state cloud fraction and more negative cloud feedback in the middle and high latitude Southern Hemisphere. We investigate possible reasons for these relationships by analyzing the mixed-phase

parameterizations in 26 GCMs. The atmospheric temperature where ice and liquid are equally prevalent (T5050) is used to characterize the mixed-phase parameterization in each GCM. Liquid clouds have a higher albedo than ice clouds, so, all else being equal, models with more supercooled liquid water would also have a higher planetary albedo. The lower cloud fraction in these models compensates the higher cloud reflectivity and results in clouds that reflect shortwave radiation (SW) in reasonable agreement with observations, but gives clouds that are too bright and too few. The temperature at which supercooled liquid can remain unfrozen is strongly anti-correlated with cloud fraction in the climate mean state across the model ensemble, but we know of no robust physical mechanism to explain this behavior, especially because this anti-correlation extends through the subtropics. A set of perturbed physics simulations with the Community Atmospheric Model Version 4 (CAM4) shows that, if its temperature-dependent phase partitioning is varied and the critical relative humidity for cloud formation in each model run is also tuned to bring reflected SW into agreement with observations, then cloud fraction increases and liquid water path (LWP) decreases with T5050, as in the CMIP5 ensemble.

McCoy, D.T., Dennis L. Hartmann and Mark D. Zelinka, 2017: Mixed-Phase Cloud Feedbacks. *Chapter 9 in, Mixed-Phase Clouds, ,* Elsevier , 300pp. PDF

This chapter introduces cloud feedbacks and describes salient features of their structure. 5 One particularly pronounced feature simulated by global climate models (GCMs), is the 6 contrast between the subtropics where cloud cover decreases with warming (a positive 7 feedback) and the mid- and high-latitudes where cloud albedo increases with warming (a 8 negative feedback). This increase in cloud albedo appears to be due to mixed-phase 9 clouds (MPCs) transitioning from a more ice-dominated to more liquid-dominated state. 10 The representation of this behavior in GCMs is discussed and is compared to satellite 11 observations. Observational constraints on the mixed-phase cloud feedback show that the 12 current generation of GCMs have too strong an increase in planetary albedo due to ice 13 transitioning to liquid in the mid- and high-latitudes, indicating a potential 14 underestimation of climate sensitivity. This behavior appears to be at least partially due to 15 an inability to maintain supercooled liquid water at sufficiently low temperatures.

Wall, Casey J., Dennis L. Hartmann and Po-Lun Ma, 2017: Instantaneous linkages between clouds and large-scale meteorology over the Southern Ocean in observations and a climate model. *J. Climate. ,* 30, 9455-9474. PDF (2 citations)

Instantaneous, coincident, footprint-level satellite observations of cloud properties and radiation taken during austral summer over the Southern Ocean are used to study relationships between clouds and largescale meteorology. Cloud properties are very sensitive to the strength of vertical motion in the midtroposphere, and low-cloud properties are sensitive to estimated inversion strength, low-level temperature advection, and sea surface temperature. These relationships are quantified. An index for the meteorological anomalies associated with midlatitude cyclones is presented, and it is used to reveal the sensitivity of clouds to the meteorology within the warm and cold sectors of cyclones. The observed relationships between clouds and meteorology are compared to those in the Community Atmosphere Model, version 5 (CAM5), using satellite simulators. Low clouds simulated by CAM5 are too few, are too bright, and contain too much

ice. In the cold sector of cyclones, the low clouds are also too sensitive to variations in the meteorology. When CAM5 is coupled with an updated boundary layer parameterization known as Cloud Layers Unified by Binormals (CLUBB), bias in the ice content of low clouds is dramatically reduced. More generally, this study demonstrates that examining the instantaneous time scale is a powerful approach to understanding the physical processes that control clouds and how they are represented in climate models. Such an evaluation goes beyond the cloud climatology and exposes model bias under various meteorological conditions

Wall, C.J., D.L. Hartmann, M.M. Thieman, W.L. Smith Jr. and P. Minnis, 2018: The lifecycle of anvil clouds and the top-of-atmosphere radiation balance over the tropical west Pacific. *J. Climate.* , 31 , 10059-10080, doi:10.1175/C+JCLI-D-18-0154.1submitted. PDF (1 citation)

Observations from a geostationary satellite are used to study the life cycle of mesoscale convective systems (MCS), their associated anvil clouds, and their effects on the radiation balance over the warm pool of the tropical western Pacific Ocean. In their developing stages, MCS primarily consist of clouds that are optically thick and have a negative net cloud radiative effect (CRE). As MCS age, ice crystals in the anvil become larger, the cloud top lowers somewhat, and cloud radiative effects decrease in magnitude. Shading from anvils causes cool anomalies in the underlying sea surface temperature (SST) of up to 20.68C. MCS often occur in clusters that are embedded within large westward-propagating disturbances, and therefore shading from anvils can cool SSTs over regions spanning hundreds of kilometers. Triggering of convection is more likely to follow a warm SST anomaly than a cold SST anomaly on a time scale of several days. This information is used to evaluate hypotheses for why, over the warm pool, the average shortwave and longwave CRE are individually large but nearly cancel. The results are consistent with the hypothesis that the cancellation in CRE is caused by feedbacks among cloud albedo, large-scale circulation, and SST.

Wall, C.J. and D.L. Hartmann, 2018: Balanced cloud radiative effects across a range of dynamical conditions over the tropical west Pacific. *Geophys. Res. Lett.* , doi:10.1029/2018GL080046.PDF (3 citations)

The high-cloud systems that are found over warm tropical oceans typically contain thick, rainy clouds connected to thinner extended ice clouds. The thick clouds have a cooling effect on Earth's climate because of their ability to reflect incoming sunlight back to space, while the thin clouds have a warming effect because of their ability to trap outgoing thermal infrared radiation. These warming and cooling effects cancel one another very closely, but why they do so is unknown. In this study we use satellite data to show that the cancellation is maintained as the large-scale atmospheric circulation varies. We also show that a state-of-the-art climate model does not reproduce this behavior.

Instantaneous relationships between clouds and large-scale vertical motion are used to study the impact of circulation on the near cancellation of cloud radiative effects that is observed over the tropical west Pacific Ocean. The coverage of deep-convective clouds increases with stronger upward motion, but the proportion of thick, medium, and thin anvil cloud remains nearly constant. Thus, when averaging over scales larger than individual storms, the top-of-atmosphere net radiation is only weakly sensitive to the large-scale flow. The balance in cloud radiative

effects is therefore maintained across a wide range of large-scale circulations. The ability of the Community Atmosphere Model Version 5 to reproduce the observed cloud-circulation relationships is investigated. The simulated convective clouds substantially overestimate the proportion of deep and optically thick cloud and underestimate the proportion of anvil cirrus. These results demonstrate that simulating key properties of deep-convective clouds remains challenging for some state-of-the-art climate models.

Hartmann, D.L., Blaz Gasparini, Sara E. Berry and Peter N. Blossey, 2018: The Life Cycle and Net Radiative Effect of Tropical Anvil Clouds. *J. Adv. Mod. Earth Sys.* , 10 ,3012-3029, doi.org/10.1929/2018MS001484. PDF (1 citation)

We explore the importance of the life cycle of detrained tropical anvil clouds in producing a weak net cloud radiative effect (NCRE) by tropical convective systems. We simulate a horizontally homogeneous elevated ice cloud in a 2-D framework using the System for Atmospheric Modeling cloud-resolving model. The initially thick cloud produces a negative NCRE, which is later canceled by a positive NCRE as the cloud thins and rises. Turning off interactive cloud radiation reveals that cloud radiative heating and in-cloud convection are fundamental in driving net radiative neutrality. In-cloud convection acts to thin initially thick anvil clouds and loft and maintain thin cirrus. The maintenance of anvil clouds is tied to the recycling of water vapor and cloud ice through sublimation, nucleation, and deposition as air parcels circulate vertically within the cloud layer. Without interactive radiation, the cloud sediments and sublimates away, producing a large negative NCRE. The specification of cloud microphysics substantially influences the cloud's behavior and life cycle , but the tendency of the life cycle to produce compensating cloud radiative effects is robust to substantial changes in the microphysics. Our study shows that small-scale processes within upper level ice clouds likely have a strong influence on the NCRE associated with tropical convective cloud systems.

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(Previous GC-792)

OMB Control No.
1910-0800

PATENT CERTIFICATION

Dennis L. Hartmann, University of Washington
Contractor

☐ Interim Certification

☒ Final Certification

DE-SC0012580 _____
DOE Prime and/or Subcontract Nos.

Contractor hereby certifies that:

1. All procedures for identifying and disclosing subject inventions as required by the patent clause of the contract have been followed throughout the reporting period.

2. There were no subcontracts or purchase orders involving research, development, and demonstration except as follows: [State none when applicable.]

   None

3. No inventions or discoveries were made or conceived in the course of or under this contract other than the following
   (Certification includes ☐ *, does not include* ☐ *all subordinates):*
   [State none when applicable.]

   None

TITLE	INVENTOR	DATE REPORTED	DOE "S" NO.*

4. The completion date of this contract is as follows: August 14, 2019

5. The following period is covered by this certification:

08	15	2014	to	08	14	2019
Month	Day	Year		Month	Day	Year

Contractor
UNIVERSITY OF WASHINGTON

Signature
Dale Becker

Address
4333 Brooklyn Avenue NE, Box 359472
Seattle, WA 98195-9472

Date of Certification : 08/20/2019

* Also include Subcontract No. If available

TANGIBLE PERSONAL PROPERTY REPORT
SF- 428

1.Federal Agency and Organization Element to Which Report is Submitted Department of Energy	2. Federal Grant or Other Identifying Number Assigned by Federal Agency DE-SC0012580	3a. DUNS 605799469	3b. EIN 91-6001537
4. Recipient Organization (Name and complete address including zip code) University of Washington Equipment Inventory Office 4300 Roosevelt Way NE. Suite 300 Seattle, WA 98105		5. Recipient Account or Identifying Number 62-8326	
6. Attachment (Check applicable) ___ Annual Report (SF-428-A) _X_ Final (Award Closeout) Report (SF-428-B) ___ Disposition Report/Request (SF-428-C)		7. Supplemental Sheet ___ Yes _X_ No	

8. Comments

Null report.

9a. Typed or Printed Name and Title of Authorized Certifying Official Peggy Vitullo Fixed Asset Specialist	9c. Telephone *(area code, number, extension)* 206-616-4045 9d. Email address pjv37@uw.edu
9b. Signature of authorized Certifying Official Peggy Vitullo Digitally signed by Peggy Vitullo DN: cn=Peggy Vitullo, o=University of Washington, ou=Equipment Inventory Office, email=pjv37@uw.edu, c=US Date: 2019.08.20 13:14:43 -07'00'	9e. Date report submitted *(Month, Day, Year)* 20 August 2019 10. Agency use only

TANGIBLE PERSONAL PROPERTY REPORT
Final Report SF-428- B

Federal Grant or Other Identifying Number Assigned by Federal Agency (Block 2 on SF-428).

DE-SC0012580

1. **Report** (Select all that apply)

a. ___ Federally-owned Property (List on Supplemental Sheet SF-428S or recipient equivalent and complete Section 2a below.)

b. ___ Acquired Equipment with acquisition cost of $5,000 or more for which the awarding agency has reserved the right to transfer title (List on Supplemental Sheet SF-428S or recipient equivalent and complete Section 2b below.)

c. ___ Residual Unused Supplies with total aggregate fair market value exceeding $5,000 not needed for any other Federally sponsored programs or projects. *(Complete Section 2c below)*

d. __X__ None of the above

2. Complete relevant section(s)	For Agency Use Only
2a. **Federally-owned Property** *(Select one or more.)* (i) ___ Request transfer to Award _____ (ii) ___ Request Federal Agency disposition instructions (iii) ___ Other *(Provide detail in Block **3** or attach request)*	Agency response to requested disposition of Federally owned property: (i) Recipient request approved___ denied ___ (ii) Dispose in accordance with attached instructions ___.
2b. **Acquired Equipment** *(Select one or more.)* (i) ___ Request unconditional transfer of title with no further obligation to the Federal Government. (ii) ___ Request Federal Agency disposition instructions Note: If the awarding agency does not provide disposition instructions within 120 days the recipient may continue to use the equipment for Federally supported projects or dispose in accordance with the applicable property standards.	Agency response to requested disposition of acquired equipment:: (i) Recipient request approved___ denied ___ (ii) Dispose in accordance with attached instructions ___

Authorized Awarding Agency Official	
Signature:	Date:
Name:	Phone:
Title	Email

2c. **Reportable Residual Unused Supplies**

(i) __ Sale proceeds or __ Estimate of current fair market value ..... $_____

(ii) Percentage of Federal participation ..... _____%

(iii) Federal share ..... $_____

(iv) Selling and handling allowance ..... $_____

(v) **Amount remitted to the Federal Government**..... $_____

3. Comments

Null report. No equipment was acquired under this award.

FINAL REPORT ATTACHMENT TO SF-428

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